FATIGUE CRACK PROPAGATION IN FRESHWATER ICE

FINAL REPORT

WILFRID A. NIXON AND LARRY J. WEBER

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13. ABSTRACT (Maximum 200 words)

The study describes an investigation of the fracture toughness and fatigue behavior of granular and columnar S2 freshwater ice. A four point bend single edge notched beam specimen was used throughout.

The fracture toughness of columnar ice was found to be temperature independent between -5 and -45°C. In contrast, granular ice exhibited a higher toughness than columnar ice between -5 and -20°C. At -45°C, granular ice had the same toughness as the columnar ice. The differences in behavior are due to micro-structural differences in the two ice types, as shown by scanning electron micrography.

The internal friction response of the granular and columnar ice was determined as a function of both frequency and amplitude. The results are consistent with a Granato-Lucke type dislocation damping model. A new technique has been developed to measure sub-critical crack growth in ice, using a low powered laser mounted on an X-Y vernier. Fatigue crack growth in ice has been observed and quantified. Three stages are evident: Initial growth may be termed classic ductile fatigue. This is followed by a period of brittle fatigue, then finally by crack arrest. The final two stages develop as the crack becomes shielded by cycling dislocations.

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FOREWORD

This study describes work that investigates fracture toughness and fatigue of randomly oriented granular and vertically oriented columnar S2 freshwater ice. The ice was manufactured and tested under laboratory conditions. Both fracture toughness and fatigue tests were performed in four-point-bending with a single-edge-notched beam specimen.

Effects of loading rate and temperature on the fracture toughness of ice were determined. It was concluded that a loading rate of 40 kPa√m s-1 was sufficiently high for valid fracture toughness measurements in ice. Vertically oriented columnar ice showed no variation with temperature in the range -5° to -45°C. Fracture toughness of granular ice was independent of temperature between -5° and -20°C, but was higher than the fracture toughness of columnar ice in the same temperature range. At a temperature of -45°C the fracture toughness of both ice types was the same. The effect of temperature on fracture toughness was explained by close examination of fracture surfaces with a scanning electron microscope.

Cyclic loading experiments were conducted to determine the frequency and strain amplitude components of internal friction for freshwater ice with a single dominant crack. Results are explained by a dislocation based damping model. A new technique has been developed to measure subcritical crack growth in freshwater ice using a low powered laser mounted on an X-Y vernier. Cyclic fatigue crack growth in ice appears to exhibit three regimes. The first is characterized by rapid crack growth by classic ductile fatigue due to high stress concentrations along a non-uniform crack front. The next stage is a period of brittle fatigue crack growth, in which local arrests of crack growth may occur. Finally, the whole crack front arrests, and, at least in these experiments, no further crack growth was observed. The final two stages appear to develop as the crack becomes increasingly shielded by cycling dislocations ahead of the crack tip.

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PROBLEM STATEMENT

The primary purpose of this project was to observe and characterize the propagation of fatigue cracks within freshwater ice. This problem has import in two main areas. The first is geophysical. The calving of icebergs from glaciers and the breakup of landfast sea ice appears to occur as a result of repeated cyclic (or fatigue) loading. Accordingly, to develop models of how such processes occur, an understanding of the fatigue behavior of ice is required. The second area in which this work has import is materials science. A number of new high strength ceramic materials are being developed for a variety of aerospace uses. Little is known about their fatigue properties at the very high temperatures at which they may be used, and study of these materials at such high temperatures is difficult and costly. Ice can be a useful analog for such high temperature ceramics, being much safer and easier to test at 95% of its absolute melting point than the ceramic materials. It also has the advantage of being transparent, thus allowing (as described below) for the observation of the whole fatigue crack front rather than just the edges of it.

While fatigue crack growth has been observed in many other materials (e.g. metals, polymers, composites, concrete), the study of fatigue in ice is relatively new. Nixon (1984) and Nixon and Smith (1987) reported some fatigue life tests on freshwater ice, but other than this, no observations of fatigue crack growth in ice had been made prior to this study. Indeed, the work of Nixon and Smith (1987) did not observe fatigue crack growth directly, but rather observed behavior typical of materials exhibiting such crack growth, namely a classic S-N or Wohler curve. Accordingly, the problem of observing and characterizing fatigue crack growth in ice comprised four sub-problems which had to be approached: 1) Measuring the fracture toughness of the ice to be used in the fatigue experiments so that appropriate K_1 loading could be applied without causing premature failure, 2) Developing a method or methods to measure the crack length in the ice accurately and repeatably, 3) determining the conditions (of frequency, load amplitude etc.) under which crack growth would occur, and 4) actually observing and characterizing the fatigue crack growth, having determined under what conditions of loading and frequency it occurred.

SUMMARY OF RESULTS

Two types of ice were tested in this project, both being freshwater ice. The first, termed granular polycrystalline freshwater ice (referred to as granular ice below) was made according to the method of Cole (1985). This ice type can be thought of as a collection of approximately spherical ice crystals or grains packed together. The sizes of the grains are very uniform and the crystallographic c-axes of the grains are randomly oriented. The grain size of the granular ice used in the project was measured to be 1.5 ± 0.5 mm by the linear intercept method.

The second ice type tested was columnar freshwater ice. This was grown in the ice towing tank at the Iowa Institute of Hydraulic Research (IIHR) by the wet seed method. The tank of water was cooled to a slightly supercooled temperature, and then the air above the tank was seeded with a mist of fine water droplets at the freezing temperature. This results in an ice sheet of columnar ice. The ice sheet was grown to a thickness of about 6" and ice blocks were then harvested using a chain saw. The columnar ice is oriented such that the crystallographic c-axes are perpendicular to the longitudinal axis of the crystal columns, but each c-axis is randomly oriented within that plane. This ice is sometimes referred to as S2 ice (Michel and Ramseier, 1971). The column diameter for the columnar ice tested in this study was 3.5 ±0.5 mm.

Fracture Toughness Experiments

Three programs of fracture toughness testing were undertaken. The first was a series of tests on columnar ice at different loading rates to ascertain at what loading rate the ice was sufficiently linear in behavior to provide a linear elastic test. This series of tests was performed at a temperature of

-5°C and at loading rates of 40, 4.0 0.4 and 0.04 kPa√m s⁻¹. A minimum of ten tests were performed at each loading rate. The tests were all performed in load control (i.e. the test machine - an MTS Sevohydraulic machine - increase the load at a constant rate) and the fracture toughness was calculated using the result of Clausing (1969) :

$$K_{Ic} = \frac{6M_f \sqrt{a}}{bw^2} * f\left(\frac{a}{w}\right)$$

where a is crack length, b is specimen width, w is specimen height, M_f is the bending moment at failure, and the term $f\left(\frac{a}{w}\right)$ is given by:

$$f(\eta) = 1.99 - 2.47(\eta) + 12.97(\eta)^2 - 23.17(\eta)^3 + 24.8(\eta)^4$$

The sample geometry is shown in Figure 1. Each sample was instrumented so as to measure both crack mouth opening (CMOD) and near crack tip opening (NCTOD) displacement during the tests, using an MTS clip gage, and a Kaman inductance gage respectively. An instrumented sample is shown in Figure 2. Typical load - CMOD plots for the four loading rates are shown in Figure 3, while Figure 4 shows the load - NCTOD plots. From these it is apparent that at a loading rate of 40 kPa√m s⁻¹ the load displacement plots are very linear, and thus it was decided that at such loading rates a linear elastic response was being observed in the ice. The variation of the fracture toughness with loading rate is shown in Figure 5. A complete tabulation of all data relevant to these and other tests described herein is given in Weber (1993).

The second and third programs of toughness testing were conducted on columnar and granular ice respectively, at a loading rate of 40 kPa√m s-1, to determine the effects of temperature on the toughness of ice. Tests were conducted at three temperatures (-5°, -20° and -45°C) for both programs, and the results are indicated graphically in Figure 6. It is interesting to note that temperature has no effect on the toughness of columnar ice in this range, while for the granular ice, the toughness is higher at the two warmer temperatures (and approximately equal) while at -45°C the toughness for the granular ice dropped to the same value as for the columnar.

The reason for the observed behavior becomes clearer when scanning electrron micrography is used to study the fracture surface of the ice samples. The technique for taking replicas of the ice surface and the details of the sample preparation are given in Weber and Nixon (1992). Figure 7 shows the fracture surface of the granular ice as observed in the SEM after fracture at the three test temperatures. Evidence of dislocation motion is clearly present at -5 and -20°C, but absent at -45°C. Figure 8 shows micrographs from the columnar ice at the three test temperatures. Dislocation motion is not apparent at any tempereature. This suggests that in the granular ice basal dislocation motion can dissipate energy (and thus increase the fracture toughness) at the higher temperatures, but at -45°C the activation energy for such basal slip is too high and thus it does not occur to any significant degree. Conversely, in the columnar ice, the orientation of the crack tip with respect to the basal planes (see Figure 9) is such that basal slip is unlikely at best. Accordingly, there is no effect of temeprature on toughness of the columnar ice. It should be noted that this result is somewhat at odds with earlier work (e.g. Nixon and Schulson, 1987) in which a clear increase of toughness with decreasing temperature was found for granular ice.

Fatigue Crack Growth Experiments

The fatigue experiments comprised three phases. First, a reliable and accurate method of measuring crack length was developed. Then, a series of experiments was conducted to evaluate the cyclic damping characteristics of the ice samples as functions of amplitude and frequency. This

allowed the optimal conditions for fatigue crack growth to be identified. Finally, a number of tests were conducted to measure fatigue crack growth in the ice samples. Again, experiments were conducted using both granular and columnar ice, with the majority of the tests (especially in the developmental work) being conducted on columnar ice (such ice being more easily manufactured).

Measuring crack length in ice proved to be no easy task. The initial approach was to use a travelling microscope, mounted in front of the sample, so that the crack tip could be monitored (see Figure 10). This technique has been used extensively in fatigue crack growth studies in metals. In ice, however, it poses two problems. First (see Figure 11) the crack front in ice is very irregular. This means that measuring crack length at a single point is far from ideal. The behavior of that single point may not be representative of the whole crack. Secondly, because the ice is transparent, it can be very hard to focus on the same part of the crack front each time a reading is made. For this reason it was decided that a modified method of crack growth measurement was required for ice.

One way in which the averaged crack length can be determined is by measuring the compliance of the specimen. In metals this is often done by means of a back face strain gage. In ice, attaching strain gages is complex and the gages do not always provide an accurate reading (see e.g. Nixon, 1984). Accordingly, a method called the dual gage method (Veerman and Muller, 1972) was used. This takes the CMOD and the NCTOD readings and uses them to determine the location of the center of rotation of the beam. In a brittle material such as ice, this center of rotation is located at or near to the crack tip. This technique was used very successfully in the fracture toughness tests described above, and in the high rate tests, the rotation point and crack tip were in general coincident. However, in long term fatigue tests, significant creep occurs, and this inelastic deformation causes the rotation point to move away from the crack tip. Thus while this technique was valid and useful for short term tests, it was not a suitable method of measuring fatigue crack growth.

Two methods were developed to provide an accurate and repeatable measurement of crack length. The first was a point measurement (with the drawbacks that entails as indicated above). This used the travelling microscope to measure crack length, but the tip of the crack was illuminated by a small 0.5 mW solid state laser. This showed the crack tip very clearly, and also enabled the operator to return to the same part of the crack front for each measurement. The other method used a 1 mW Helium Neon laser to measure the whole crack front. This laser was mounted on two vernier scales. The first, horizontal, scale allowed the laser beam to be moved along the crack front, the second adjusted the height of the beam (see Figure 12). The amount of reflection of the beam changed significantly when the beam intersected the crack front. This allowed the whole crack front to be mapped out relatively simply (see Figure 13). A more detailed description is given in Weber and Nixon (1993). To the authors knowledge, this is the first time a complete crack front has been monitored successfully during fatigue tests, and represents a significant development in terms of monitoring cracks in ice. There will undoubtedly be applications of this technique beyond the current study.

The second phase of the fatigue crack growth experiments was to determine the conditions of amplitude and loading rate under which fatigue crack growth would be most favorable. This was done by performing a series of internal friction experiments on cracked samples. Each sample was loaded cyclically, and the energy loss per cycle (the internal friction) was determined experimentally from the load-displacement curve. It was reasoned that the higher the loss observed (i.e. the more pronounced the hysteresis), the more energy was being "pumped into" the sample for dissipation at the crack tip. Of particular importance in terms of crack growth was any residual strain at the end of the loop, which was a good indicator of possible crack growth.

This approach has been used in the study of the micro-mechanical behavior of ice by Cole (1990). However, Cole used uncracked samples of granular ice in his studies (no columnar ice was

examined). Thus, in Cole's work, the hysteretic losses were distributed throughout the sample. In this study, by comparison, it was expected that the losses would be concentrated in the region of highest stress (i.e. around the crack tip).

The internal friction, ϕ, is obtained from the load-displacement loop by the relationship:

$$\tan \phi = \frac{\Delta W}{2\pi W}$$

where W is the area beneath one loading curve and ΔW is the area within one hsyteresis loop (see Figure 14).

The internal friction analysis which follows is based on the theory of Granato and Lucke (1956). They identified two components of internal friction: ϕ_i, the frequency dependent internal friction, and ϕ_h the amplitude dependent internal friction. Ideally these two components can be seperated, but following the recommendation of Cole (1990) this has not been done, due to a limited data-set. Experiments were performed at five different frequencies (0.001, 0.01, 0.1, 1.0 and 5.0 Hz), and the internal friction was calculated from the load-displacement plots of these tests. Typical plots are shown in figure 15. The internal friction values are shown in Figure 16, along with data from Cole's (1990) study. It is apparent that, as expected, internal friction decreases as frequency increases. Put simply, at high frequencies there is less time for irreversible deformation to occur. Further, again as expected, the values of internal friction in the cracked samples are less than those observed in the uncracked, uniformly loaded samples of Cole(1990). The volume of material experiencing high stress (and thus exhibiting permanent deformation) is much less in the cracked than in the uncracked samples.

It also appears that the columnar ice exhibited somewhat higher values of internal friction than the granular ice. Other differences in behavior between the two ice types were observed. In particular, the columnar ice exhibited significant residual strain at the end of each cycle at frequencies of 0.001 and 0.01 Hz. Some of this residual strain clearly arose from crack growth (see Figure 17). In the granular ice, residual strain was only apparent at the lowest frequency (0.001 Hz), and no crack growth was visible at that time. After each series of cyclic loading (detailed in Weber, 1993) samples were loaded to fracture at 40 kPa$\sqrt{m}$ s^{-1}. The columnar ice showed a toughness marginally less than that recorded in earlier, more standard toughness tests (i.e. in which ice had not been cyclically loaded prior to toughness testing), while the granular ice showed toughnesses about 35% higher after cyclic loading than was observed in standard toughness tests. This statistically significant higher value suggests that some crack modification mechanism must have been operating in the granular ice. Candidates for such mechanisms might include crack blunting or crack tip shielding by dislocations.

A second series of experiments was performed on both columnar and granular ice to determine the effect of amplitude on the internal friction. Samples were loaded to 60kPa$\sqrt{m}$ at 0.1 Hz for ten cycles. The stress intensity was then incremented by 20 kPa$\sqrt{m}$ and held for ten cycles, repeatedly until each specimen failed. Raw data are shown in Figure 18. The variation of internal friction with amplitude is shown in Figure 19. There is little dependence of internal friction on amplitude, for either the columnar or the granular ice. However, it is very apparent that internal friction is much higher in the columnar ice.

The Granato-Lucke theory predicts that the amplitude dependent internal friction, ϕ_h, is given by:

$$\tan \phi_h = \left(\frac{C_1}{\varepsilon_0} \right) e^{\frac{-C_2}{\varepsilon_0}}$$

where C_1 and C_2 are lumped material constants. From this, it is apparent that a plot of $\varepsilon_0 \tan\phi$ against ε_0^{-1} should yield a straight line. Figure 20 shows that this is indeed the case for both granular and columnar freshwater ice.

From these tests it was concluded that the most likely conditions for fatigue crack growth in freshwater ice would occur at low frequencies. Accordingly, although some crack growth had been observed in preliminary experiments conducted at 5 Hz (Nixon and Weber, 1991), the majority of the crack growth testing was conducted at 0.01 Hz. In all, 13 fatigue tests were conducted (not including preliminary experiments) at a frequency of 0.01 Hz and a temperature of -5°C. Table 1 presents a summary of these tests. Figure 21 shows the crack growth observed in those samples for which the solid state laser (measuring growth at a point) was used. Figure 22 shows the crack profiles along the crack front for those experiments in which the He-Ne laser was used to map the whole crack front. Figure 23 shows these crack profiles with the initial crack position subtracted, thus showing total growth. From Figure 23, it is clear that initial crack growth only in a few locations (but is large at those sites), after which growth is uniform along the whole crack front. By taking the area of crack advance, and dividing by the width of the crack, an average crack growth can be computed, and this is shown for the He-Ne laser measured samples in Figure 24. This averaged growth is somewhat greater than the growth measured at a point with the solid state laser. This may be due to the fact that the solid state laser measured growth close to the surface, which (see Figure 22) is typically an area of low growth.

For all experiments, the growth occurred during the first 1,000 to 1,500 cycles. It is apparent that after this initial growth the crack tends to slow down considerably, so that any further growth is essentially unmeasurable. Micrography sheds some light on this process. Figure 25 shows the region near the crack tip of test 9. Striations are clearly present and can be seen more clearly in Figure 26, which is an enlarged view of the area. These striations are typical of classical ductile fatigue striations. The measured growth rate from the striations is 5.0×10^{-6} m/cycle, which compares well with values taken from Figure 24. Figure 27 shows the crack tip region from test 11. Again, an expanded view is given in Figure 28, and this time the striations appear somewhat different. Indeed, their appearance is typical of brittle striations (Beachem and Pelloux, 1964: Forsyth, 1963). Further, in Figure 28 the direction of growth is from top right to bottom left of the picture, and the striation spacing is clearly decreasing as the crack moves in this direction. There is also evidence that the crack has stopped and then restarted at two places marked by AA and BB in the Figure, before finally arresting at CC.

From the above, it appears that the crack goes through a phase of relatively rapid ductile fatigue crack growth, followed by a period of brittle fatigue crack growth (which may include a number of temporary arrests) prior to finally arresting. As to why the crack finally arrests, Figure 29 shows the region ahead of the crack tip in test 9. In Figure 29, clearly defined dislocation slip bands can be seen, with a "whisker" centered on most slip bands. Wei and Dempsey (1991) and Sinha (1987) report that such whiskers are produced by etching the core of a dislocation that has stopped. The location of the whisker in the slip band indicates that a large amount of to and fro dislocation motion has occurred ahead the crack tip. Ewart and Suresh (1992) state that such cyclic slip is essential for fatigue in metals, but for crack growth to occur the dislocations must interact with the crack tip. The dislocations in Figure 29 are evidently not interacting with the crack tip, but rather are dissipating energy ahead of the crack tip which might otherwise drive crack growth. Further evidence for this description of the crack tip region is apparent from the K_{Fail} values in table 1, which are much higher than the toughness values given previously.

The fatigue process in ice thus appears to consist of three phases. First, ductile fatigue crack growth occurs and is relatively rapid. As a field of dislocations starts to develop ahead of the crack tip, the mechanism of crack growth becomes more brittle in nature, and occasional arrests in crack growth may be observed. Finally, a shield of cyclically active dislocations develops around the crack tip, and further fatigue crack growth stops, or slows to a level at which it is currently undetectable.

CONCLUSIONS

On the basis of the experiments performed in this study, the following conclusions can be drawn.

1:     The apparent fracture toughness of freshwater ice increases, and the load - CMOD curve becomes increasingly non-linear, as loading rate is decreased. At a temperature of -5°C, a loading rate of 40 kPa√m s-1 is adequate to provide linear behavior in a frature toughness test.

2:     The toughness of columnar freshwater ice does not vary (at the 99% level of significance) with temperature between -5°C and -45°C.

3:     Conversely, the toughness of granular ice, while not changing between -5 and -20°C, decreases between -20 and -45°C to a value which is statistically indistinguishable from the toughness value for columnar ice at that temperature.

4:     The behavior of the toughness of these two ice types with temperature has been explained by the use of scanning electron microscopy, which has allowed dislocation activity to be observed.

5:     Two new methods of measuring the crack length in an ice fatigue sample have been developed. One of these allows the whole crack front to be mapped out throughout a test.

6:     Through a series of experiments in which loading amplitude and frequency were varied, it has been determined that both granular and columnar freshwater ice samples with single dominant cracks present exhibit hysteretic behavior which is consistent, as far as can be determined, with the Granato - Lucke theory of internal friction and damping.

7:     For the first time, unequivocal measurements of fatigue crack growth in ice have been made.

8:     The fatigue crack growth behavior of ice appears to exhibit three phases. First, rapid, apparently ductile crack growth, then what has been described in other materials as brittle fatigue crack growth with occasional arrests and re-initiations, followed finally by a complete arrest, after which no further crack growth was observed in these experiments. It appears that the final arrest is caused by the development of a shield of dislocations some distance ahead of the crack tip itself.

This study has allowed a considerable amount of knowledge to be developed concerning fatigue crack growth in freshwater ice. Nonetheless, a number of areas require further investigation. However, the techniques developed herein will allow that further study to be made with comparative ease.

TABLE 1: SUMMARY OF FATIGUE TEST RESULTS

Test #	Ice Type	K_{max} kPa√m	Total Cycles	Total Growth (mm)	K_{Fail} kPa√m	Technique
3	Columnar	90	3231	0.737	204	TM-SSL
4	Columnar	90	1649	0.462	161	TM-SSL
5	Columnar	110	1839	0.137	129	TM-SSL
6	Columnar	130	3313	0.208	143	TM-SSL
7	Columnar	150	22	0.015	134	TM-SSL
8	Columnar	150	0	0.000	130	TM-SSL
9	Columnar	90	1555	1.930	147	HN Laser
10	Columnar	110	4945	0.914	166	HN Laser
11	Columnar	130	1743	1.020	201	HN Laser
12	Granular	105	451	no data	158	HN Laser
13	Granular	105	1717	no data	192	HN Laser
14	Granular	90	1524	0.162	no data	TM-SSL
15	Columnar	90	1905	0.406	147	HN Laser

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PUBLICATIONS ARISING FROM THE STUDY

Nixon, W.A. and Weber, L.J. (1991). Fatigue-crack growth in freshwater ice: preliminary results. *Annals of Glaciology*, vol. 15, pp.236-241.

Weber, L.J. and Nixon, W.A. (1991). Crack opening and propagation in S2 freshwater ice. In *Proceedings of the Tenth International Conference on Offshore Mechanics and Arctic Engineering*, vol. 4, pp. 245-252.

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PUBLICATIONS IN PREPARATION

Weber, L.J. and Nixon, W.A. Fracture Toughness of Freshwater Ice. Iowa Institute of Hydraulic Research Internal Report in preparation.

Weber, L.J. and Nixon, W.A. Fatigue Crack Growth in Freshwater Ice. Iowa Institute of Hydraulic Research Internal Report in preparation.

Weber, L.J. and Nixon, W.A. Temperature and loading rate effects on the fracture toughness of freshwater ice. In preparation for submission to a Journal.

Weber, L.J. and Nixon, W.A. Crack opening behavior in freshwater ice. In preparation for submission to a Journal.

Weber, L.J. and Nixon, W.A. Internal friction and fatigue crack growth in freshwater ice. In preparation for submission to a Journal.

FIGURES
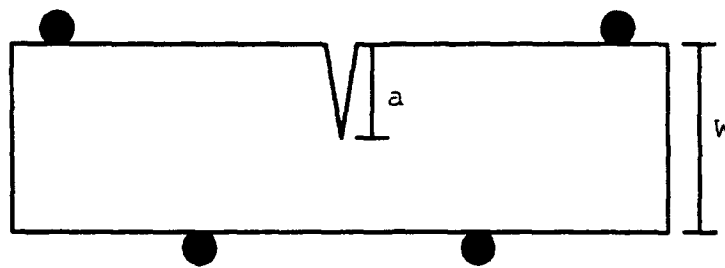
Figure 1. Four-Point-Bend Configuration.
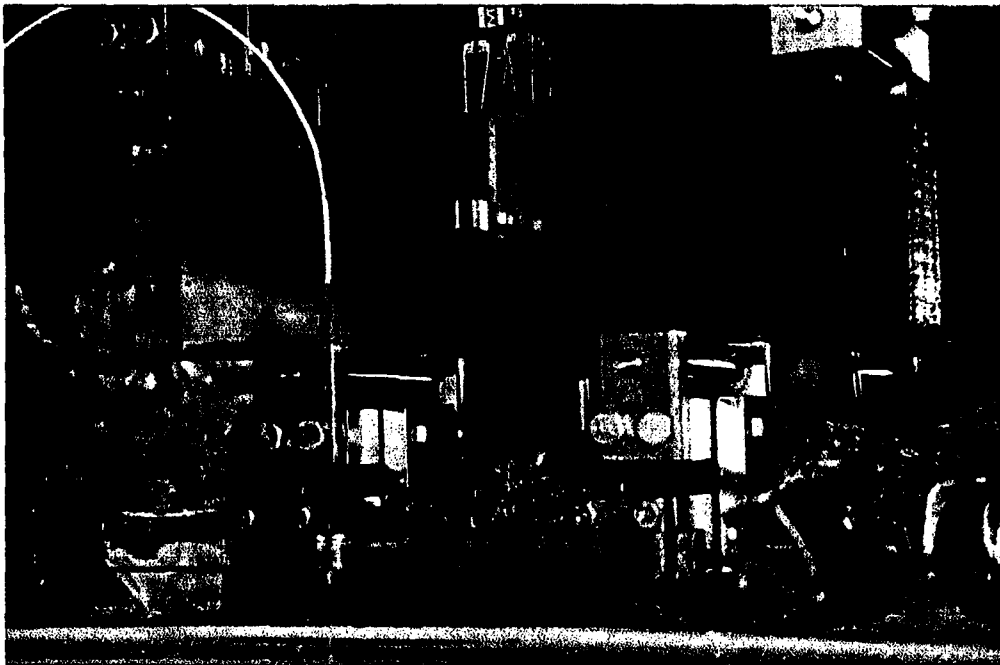
Figure 2. Instrumented Test Sample
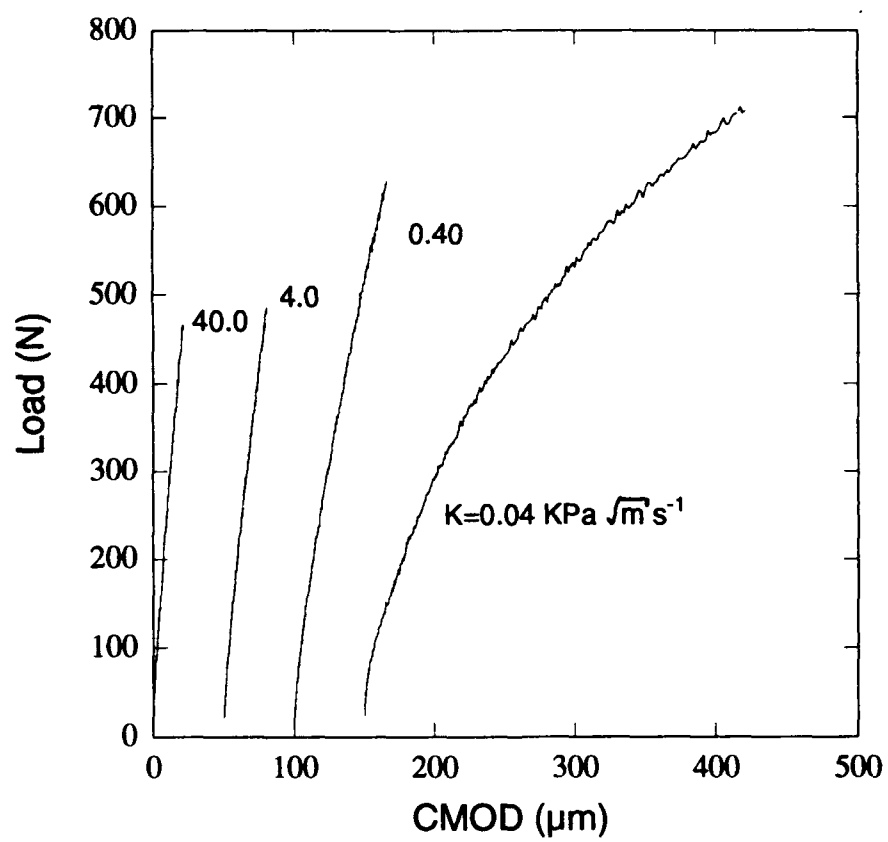
Figure 3: Typical Load - CMOD Plots for Toughness Tests
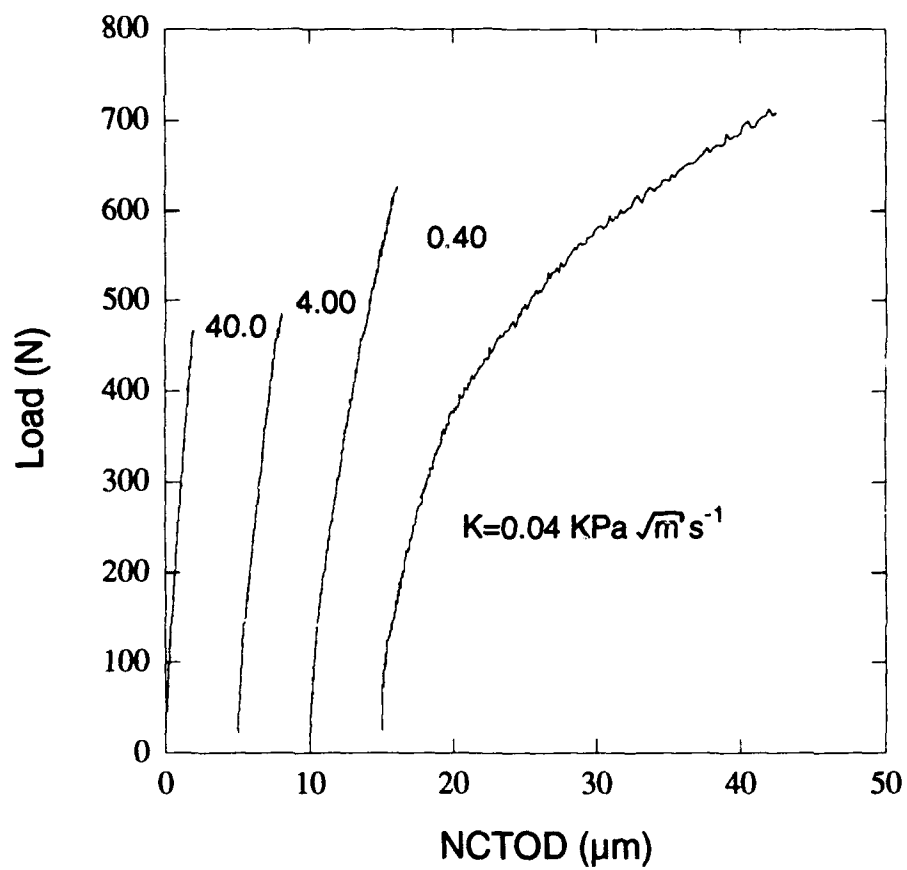
Figure 4: Typical Load - NCTOD Plots for Toughness Tests
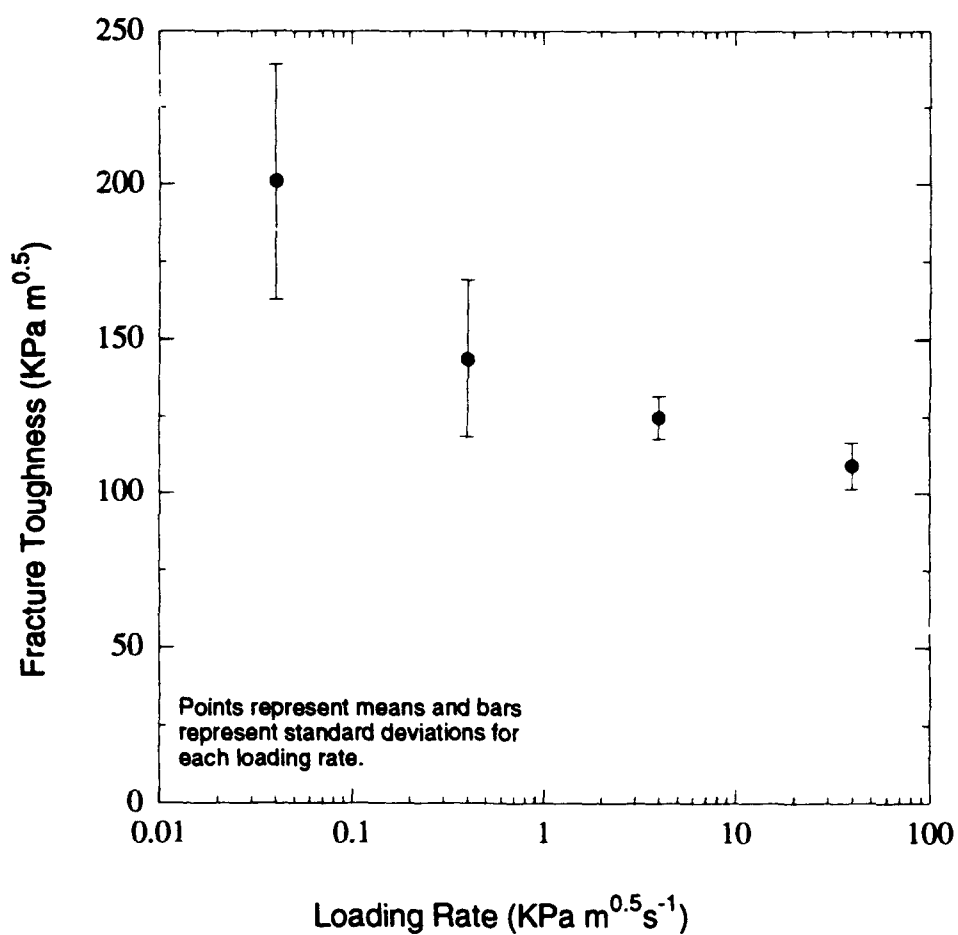
Figure 5: Variation of Toughness with Loading Rate for Columnar Freshwater Ice
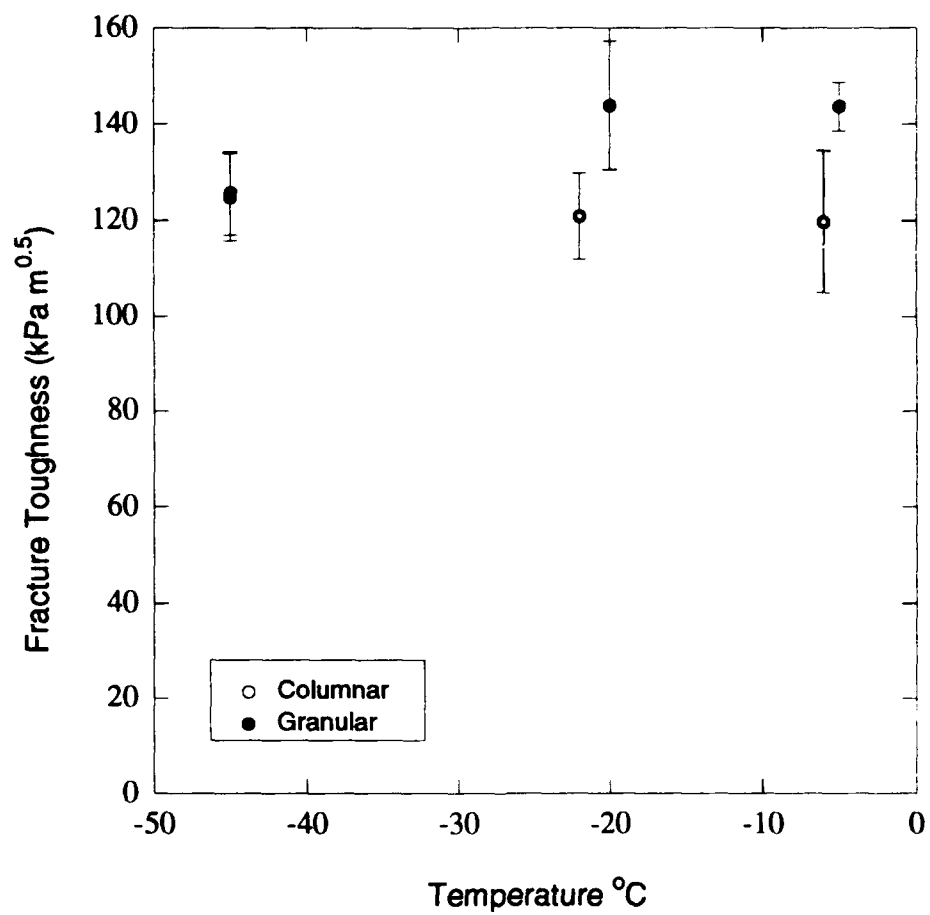
Figure 6: Variation of Toughness with Temperature for Granular and Columnar Freshwater Ice
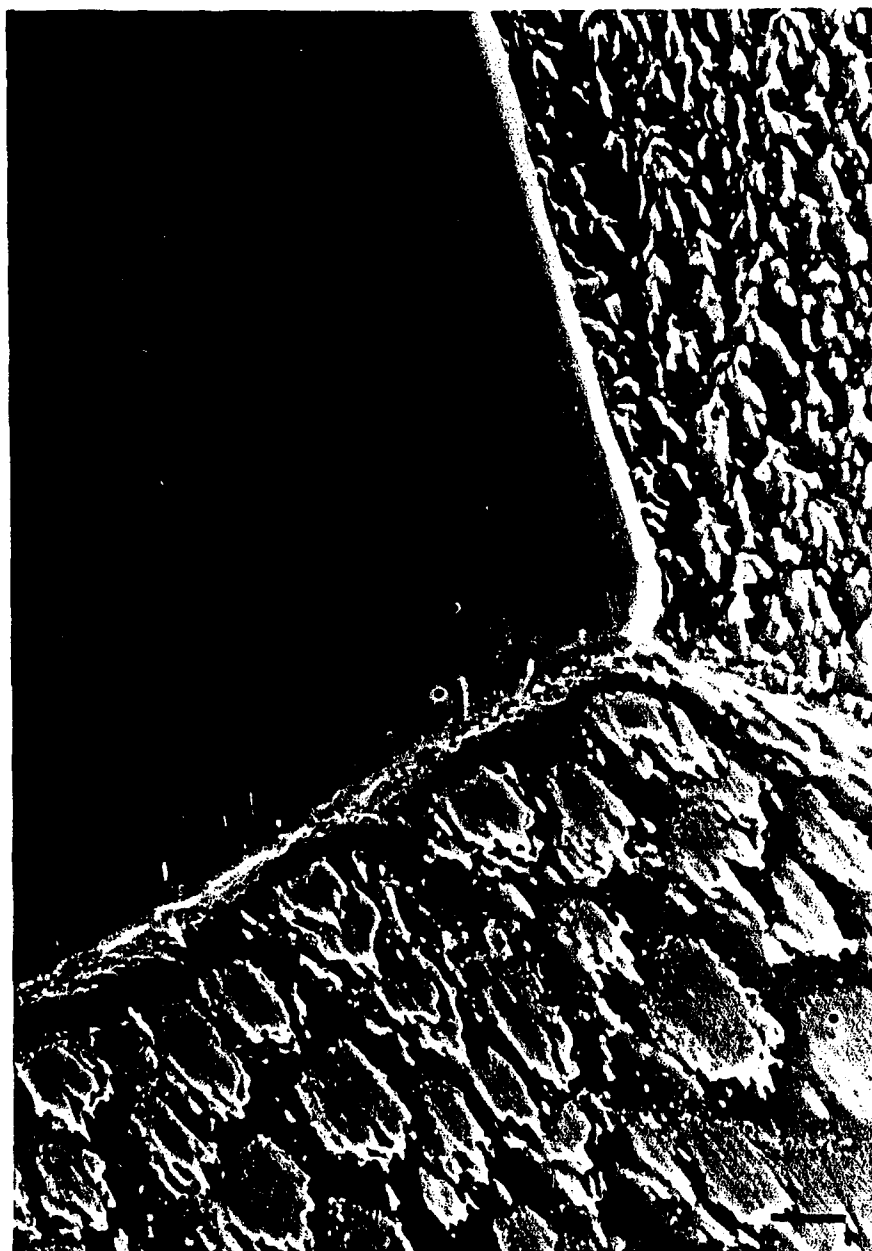
Figure 7a: Micrograph of Fracture Surface from Toughness Test of Granular Ice at -5°C

Figure 7b: Micrograph of Fracture Surface of Toughness Test of Granular Ice at -20°C
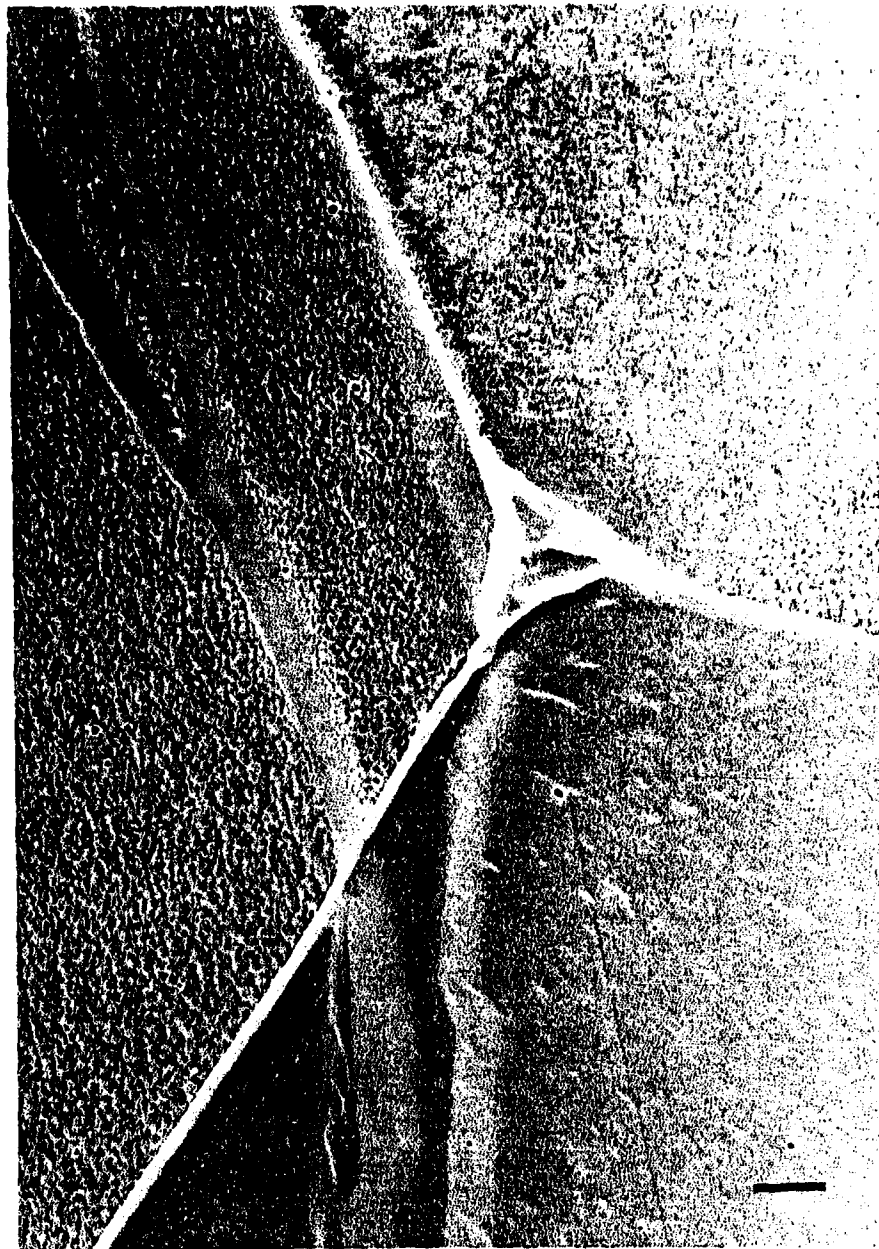
Figure 7c: Micrograph of Fracture Surface from Toughness Test of Granular Ice at -45°C
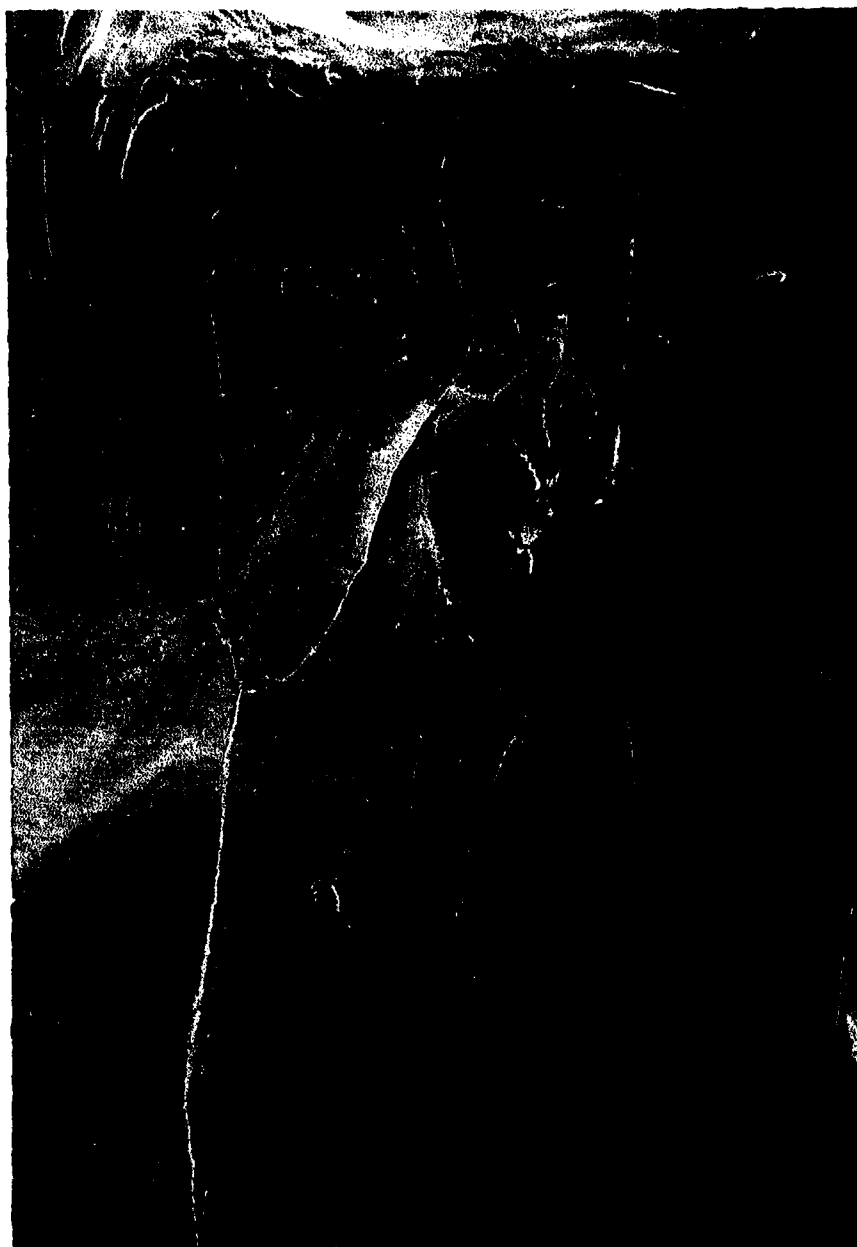
Figure 8a: Micrograph of Fracture Surface from Toughness Test of Columnar Ice at -5°C

Figure 8b: Micrograph of Fracture Surface from Toughness Test of Columnar Ice at -20°C

Figure 8c: Micrograph of Fracture Surface from Toughness Test of Columnar Ice at -45°C
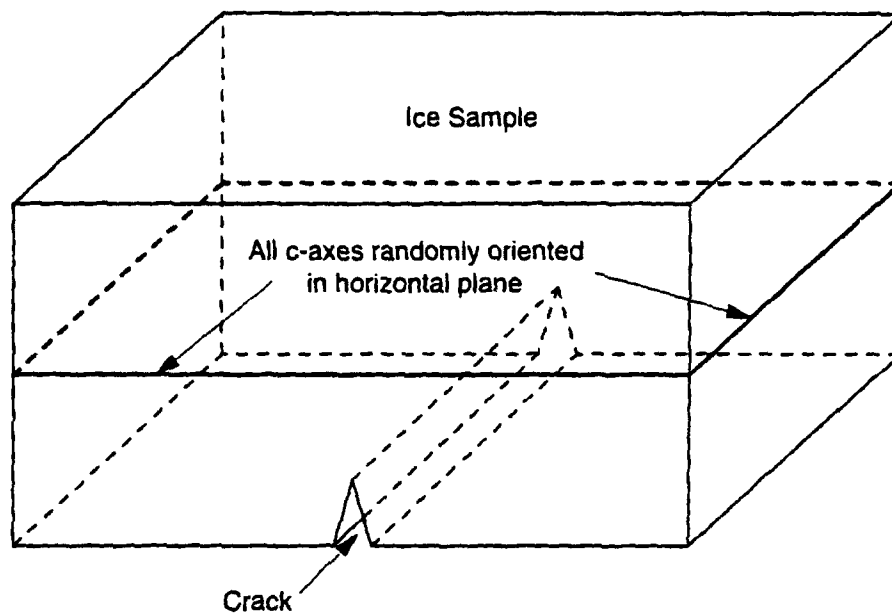
Figure 9: Orientation of C-axis Relative to Crack Front in Columnar Ice
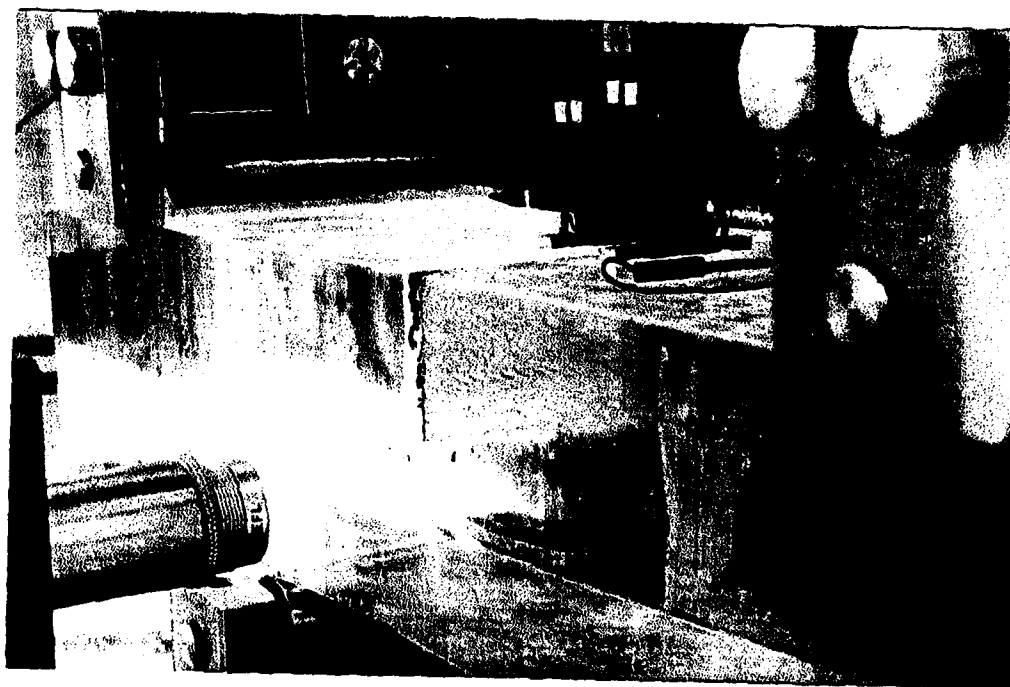
Figure 10: Fatigue Sample with Travelling Microscope for Crack Measurement
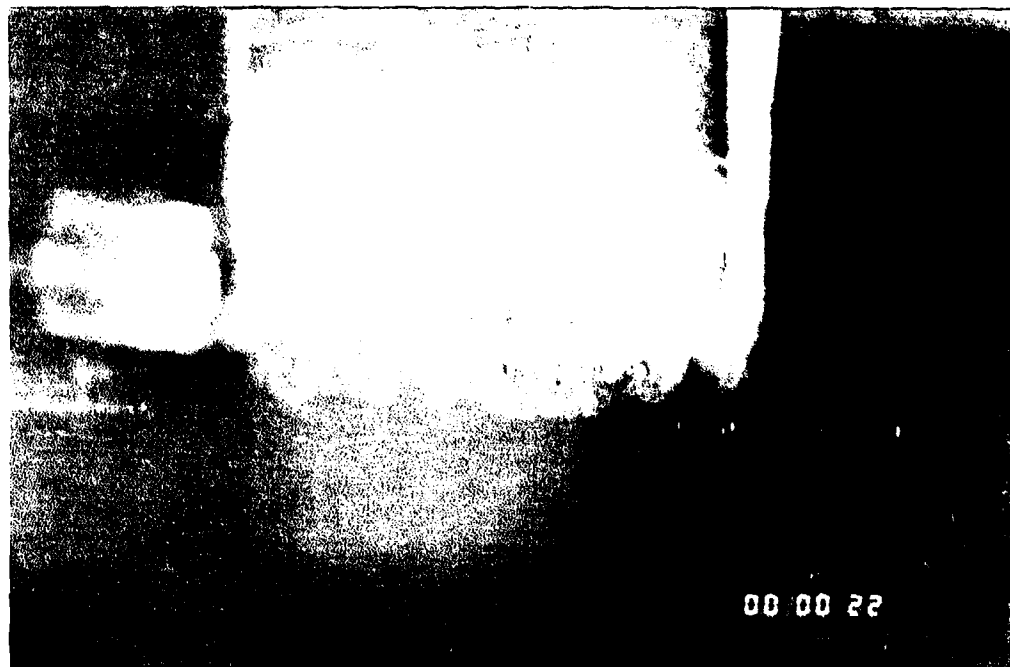
Figure 11: Irregular Crack Front in Ice

Figure 12: Laser Measuring System for Fatigue Cracks in Ice
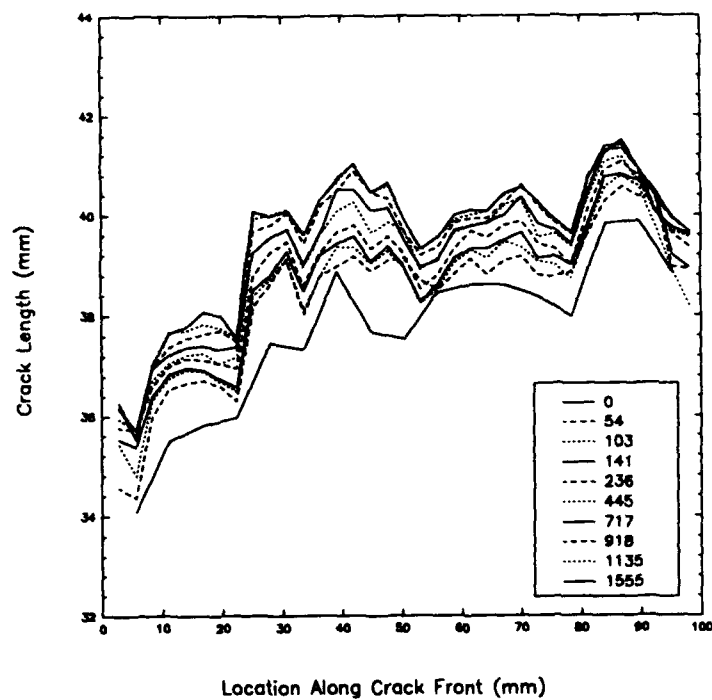
Figure 13: Fatigue Crack Front in Ice as Mapped with Laser System
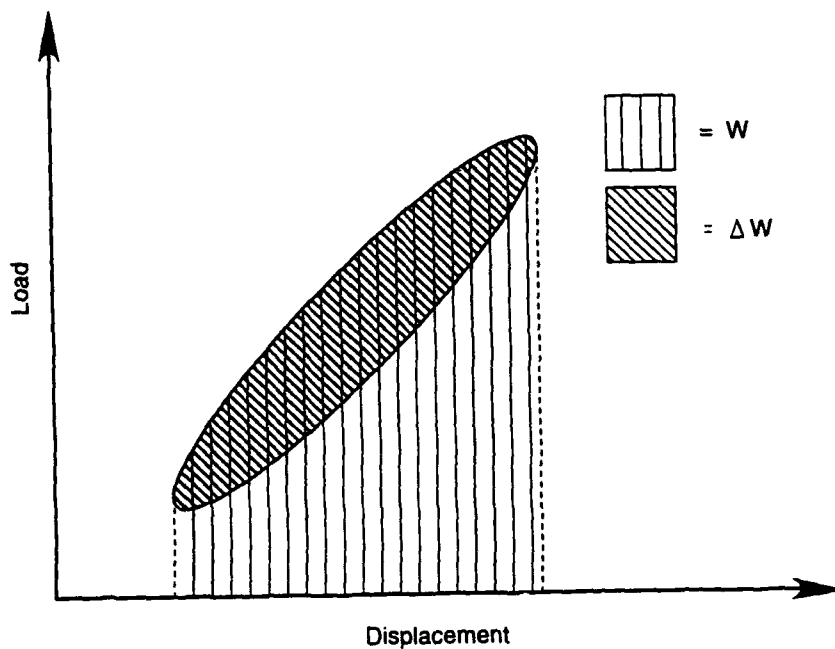
Figure 14: Graphical Definition of Internal Friction, ϕ
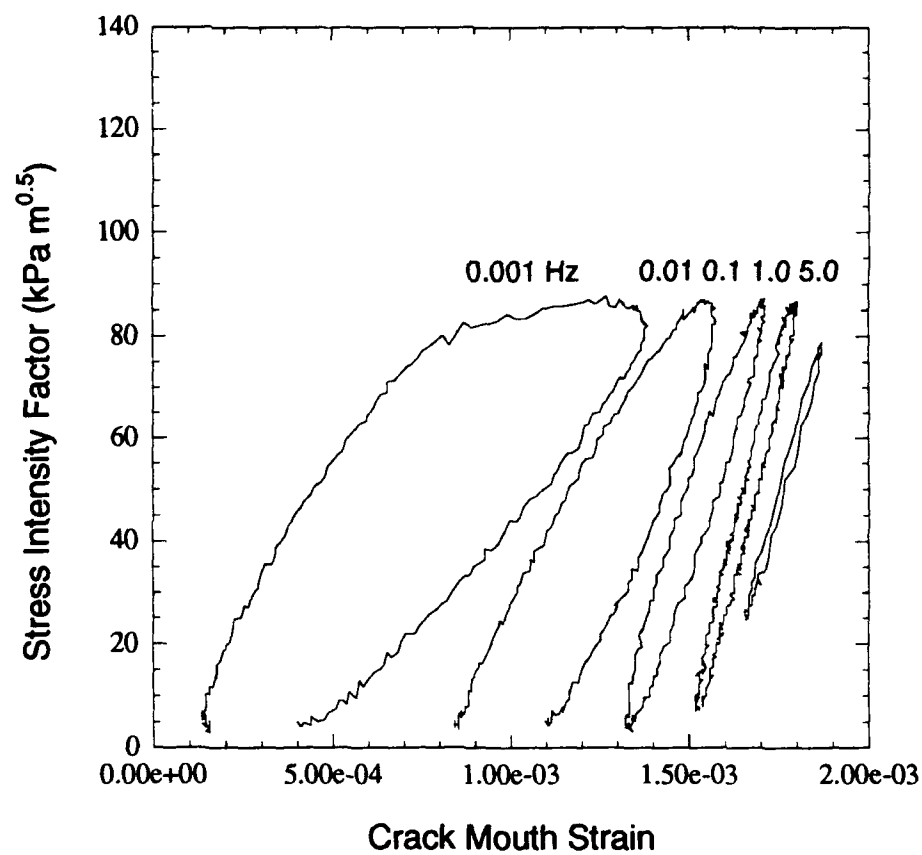
Figure 15a: Hysteresis Loops For Columnar Ice As A Function Of Frequency
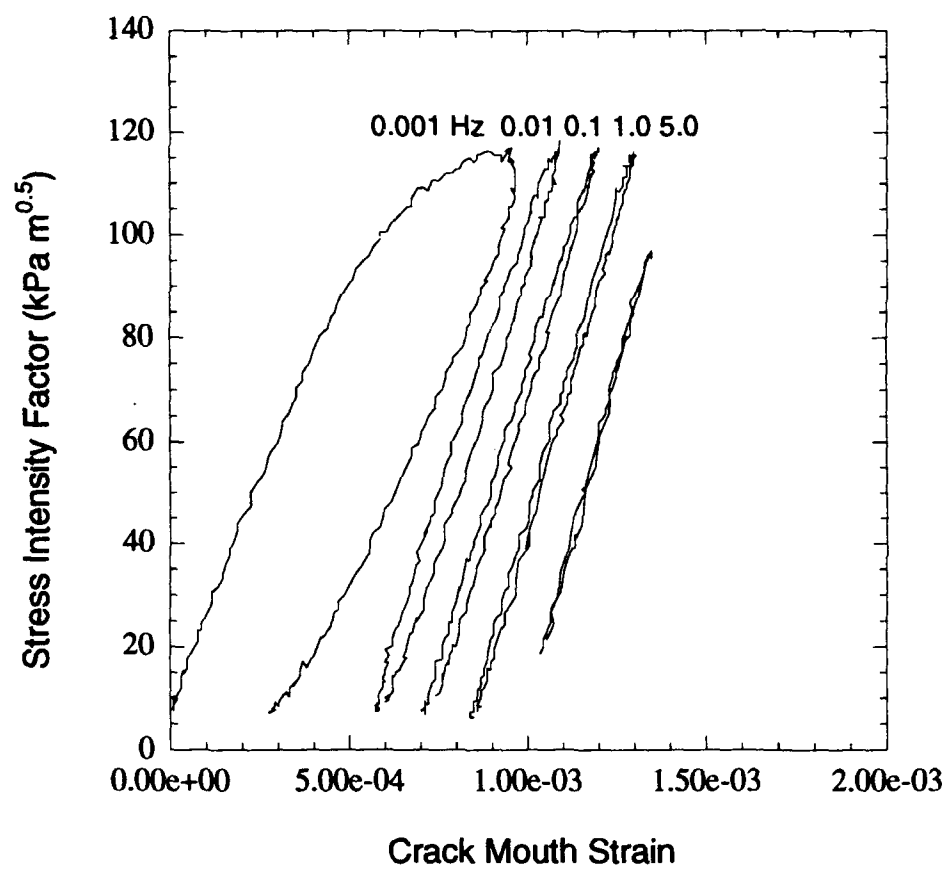
Figure 15 b: Hysteresis Loops for Granular Ice as a Function of Frequency
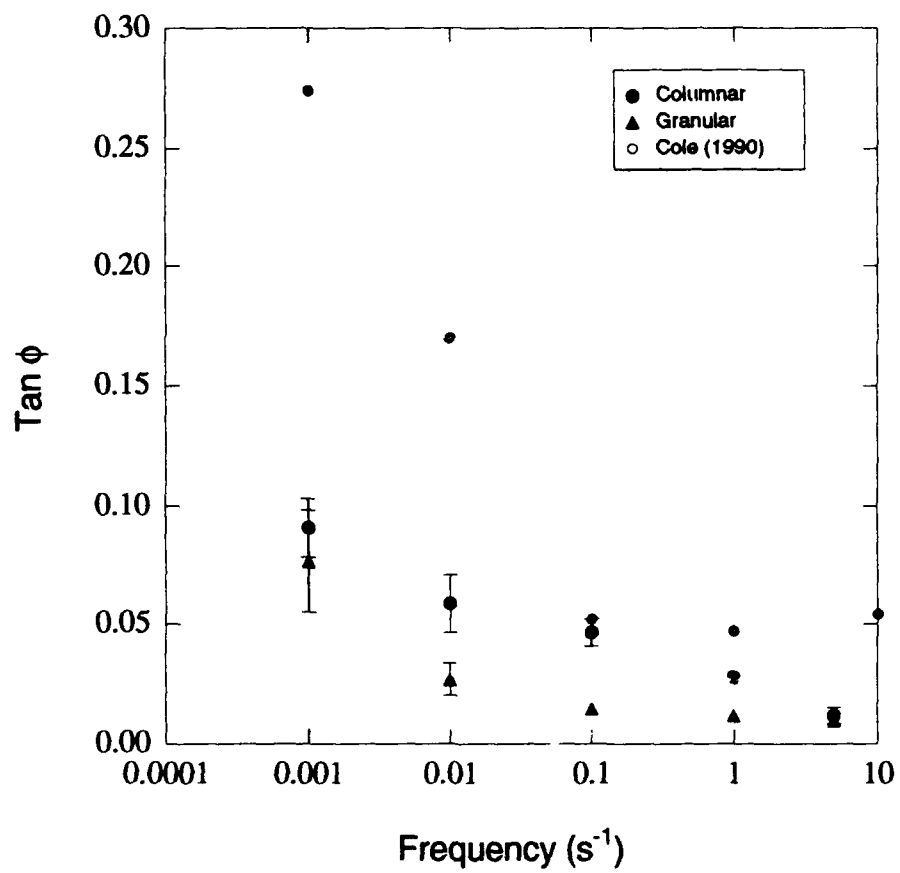
Figure 16: Variation of Internal Friction with Frequency

Figure 17: Crack Growth in Columnar Ice at Low Frequency
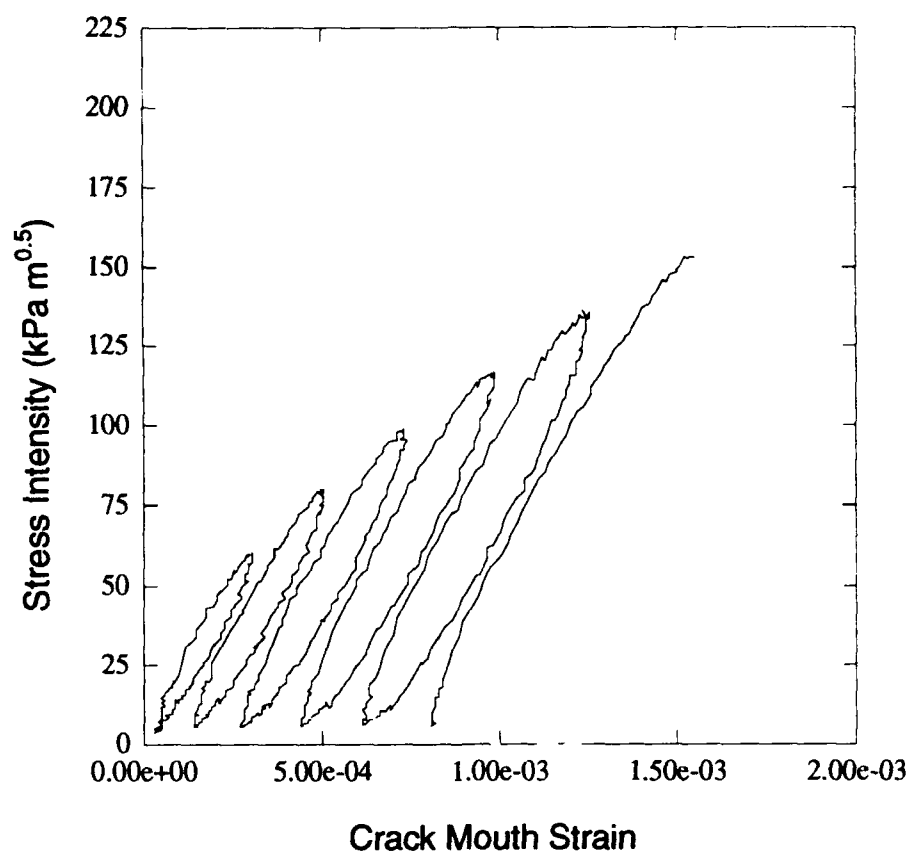
Figure 18a: Hysteretic Behavior of Columnar Ice as a Function of Amplitude
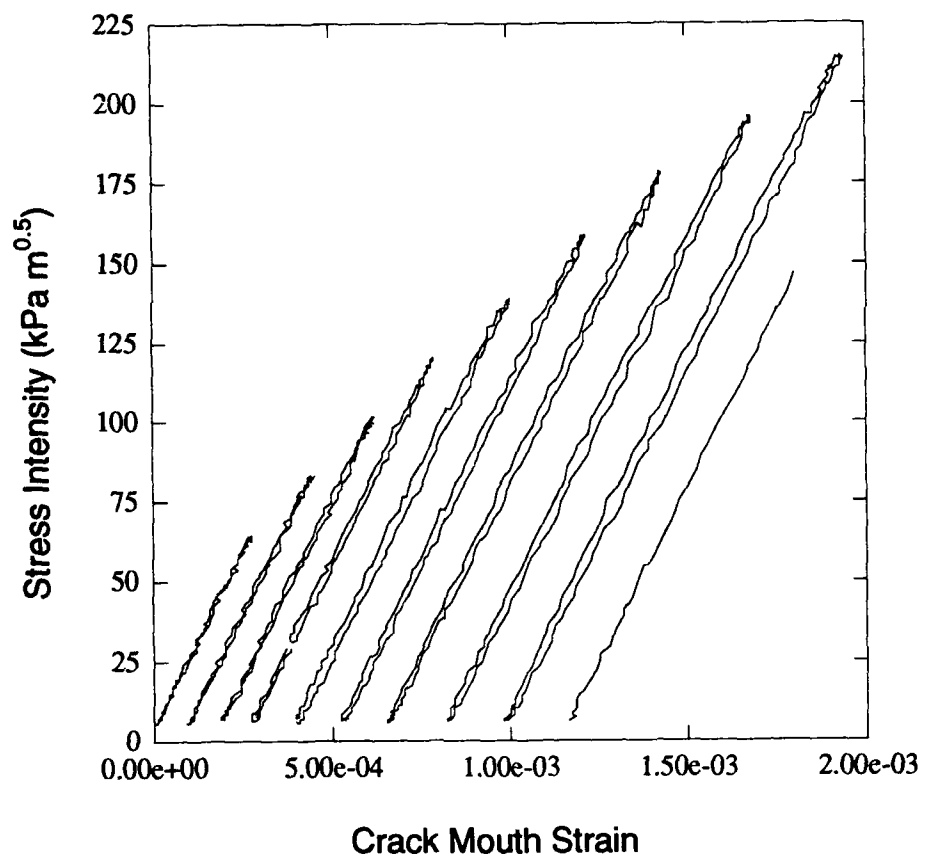
Figure 18b: Hysteretic Behavior of Granular Ice as a Function of Amplitude
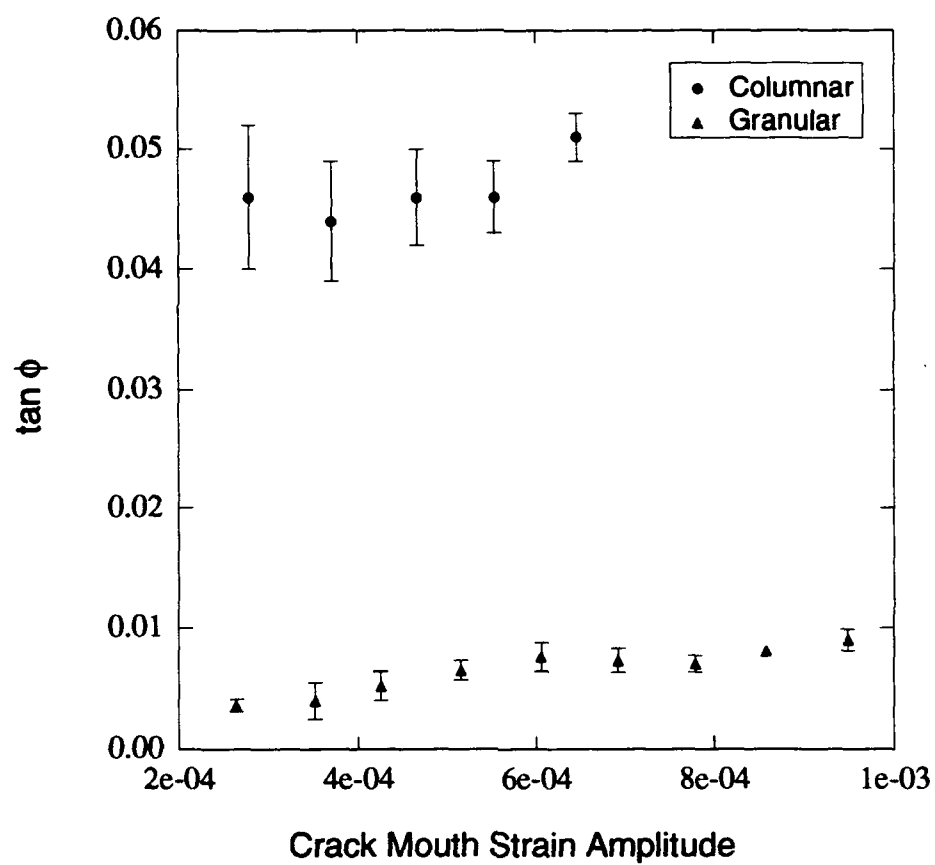
Figure 19: Variation of Internal Friction with Amplitude
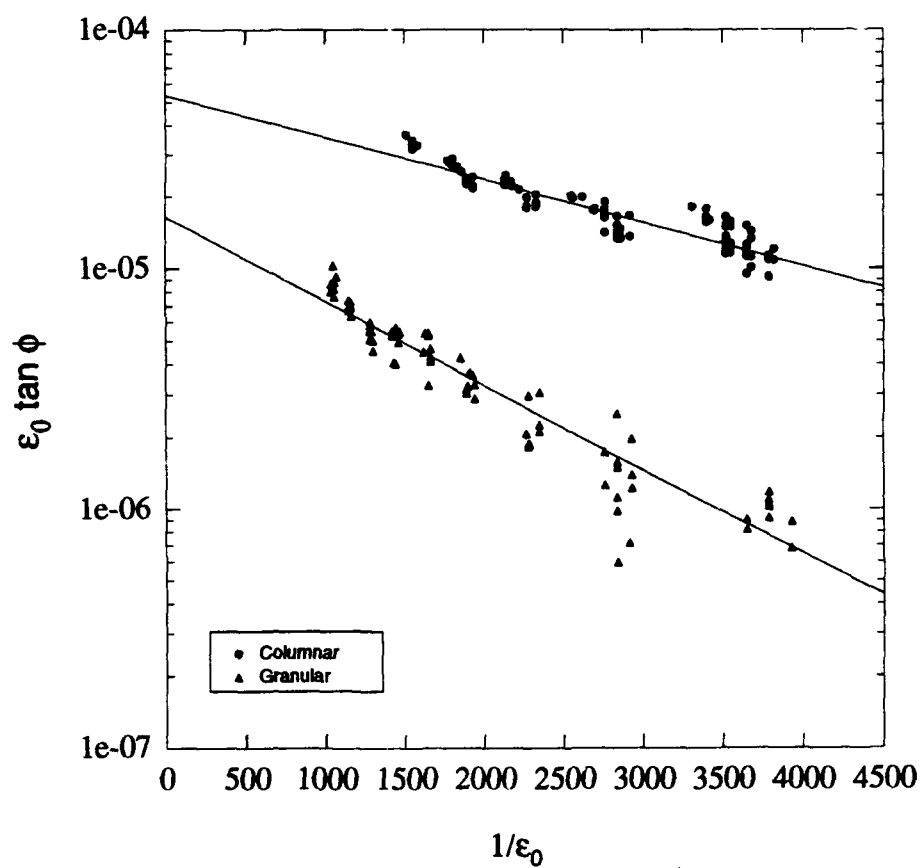
Figure 20: Granato - Lucke Plot for Granular and Columnar Ice
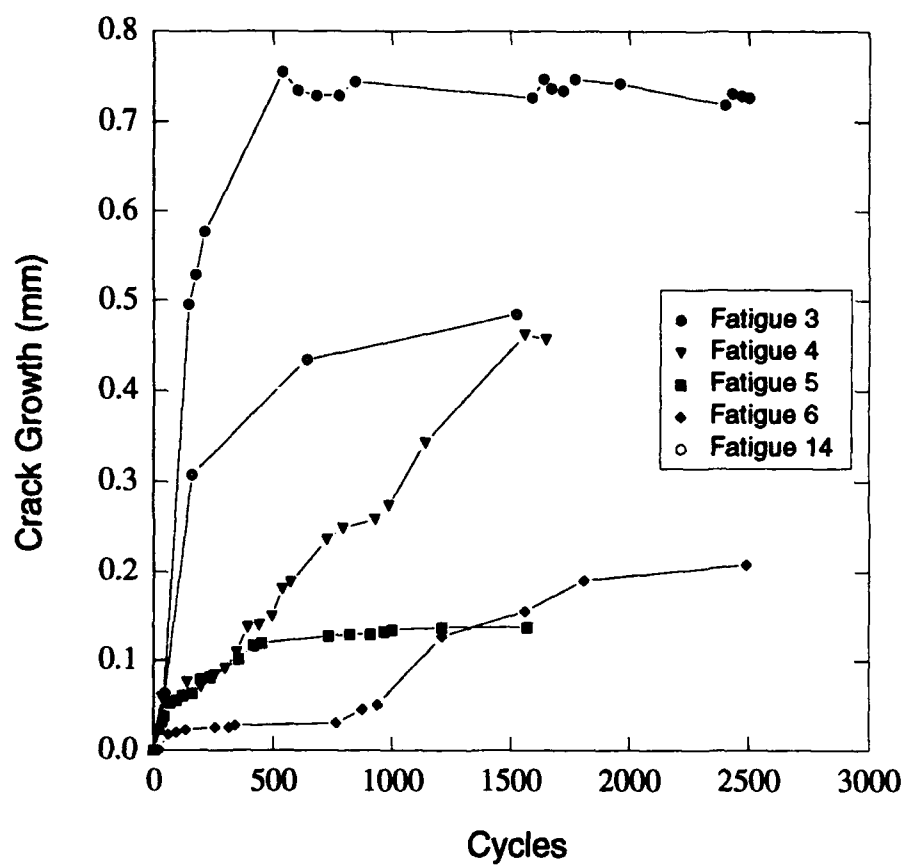
Figure 21: Fatigue Crack Growth in Ice Measured at a Point
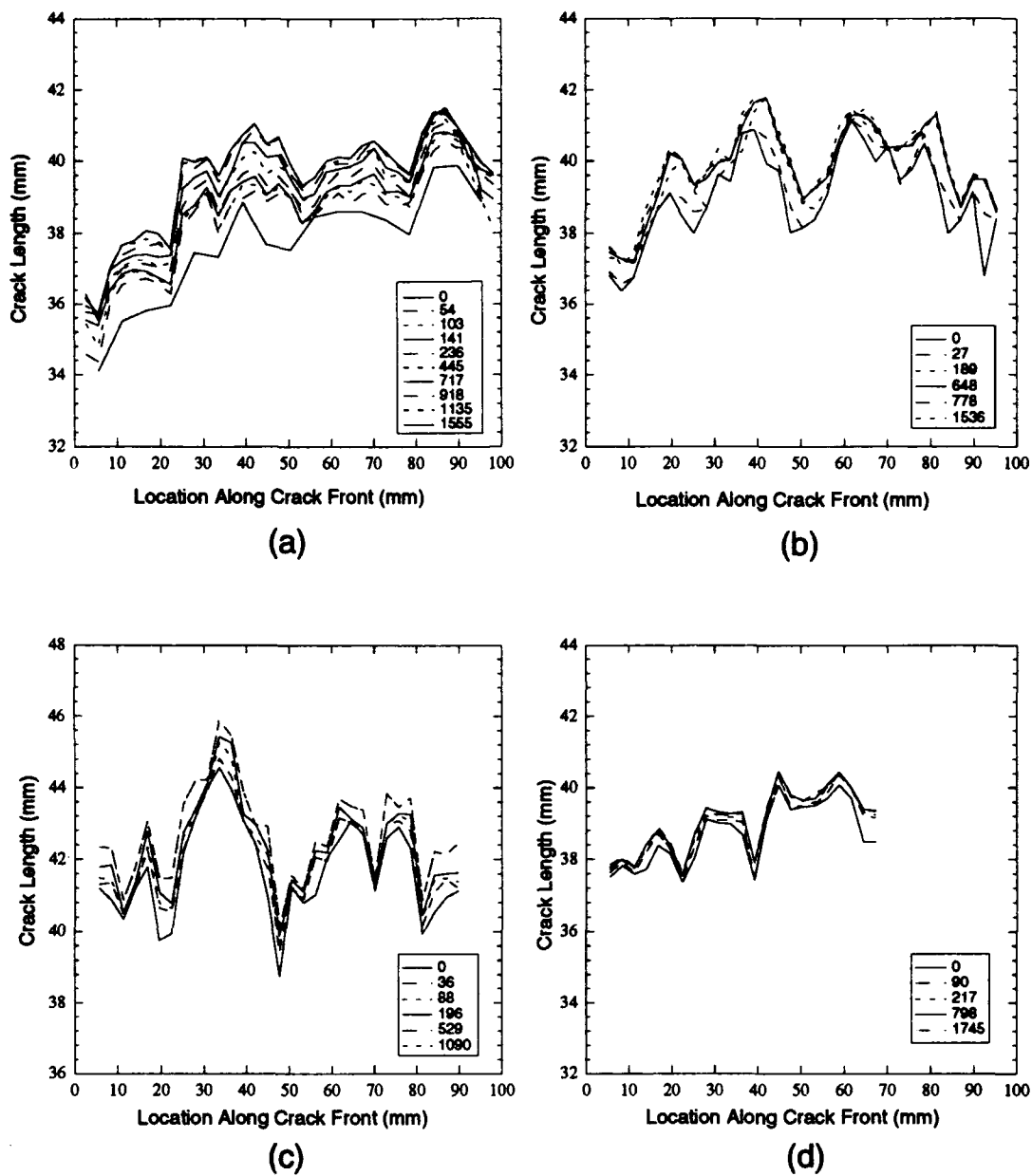
Figure 22: Crack Profiles for Experiments Using the Helium - Neon Laser. (a) Fatigue 9, (b) Fatigue 10, (c) Fatigue 11 and (d) Fatigue 15.
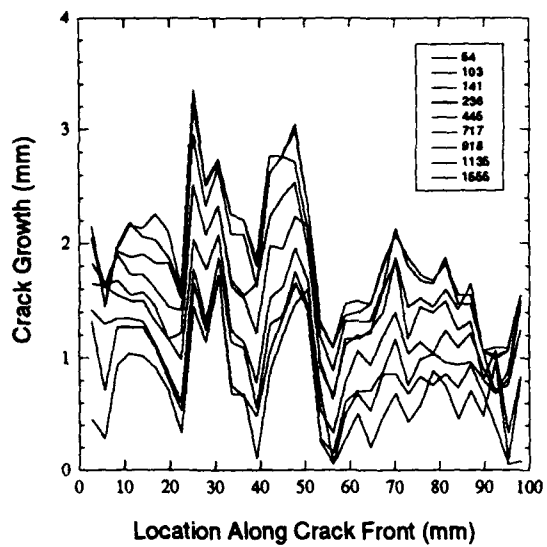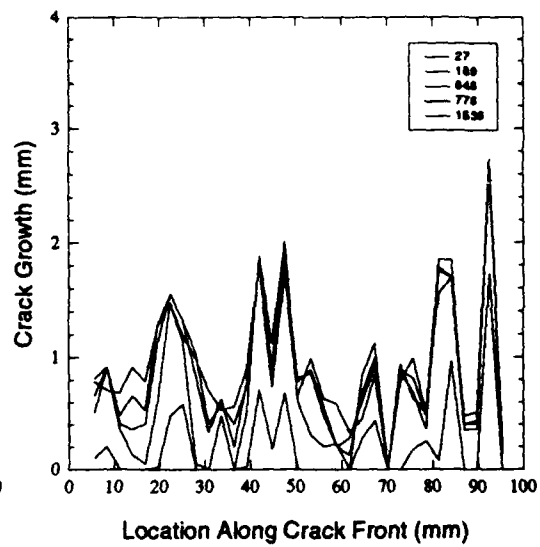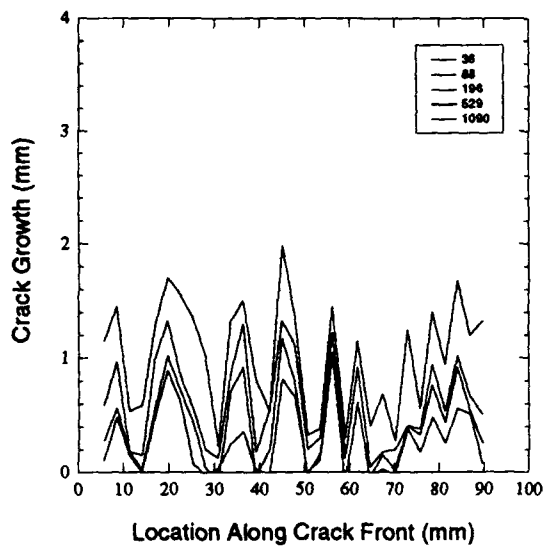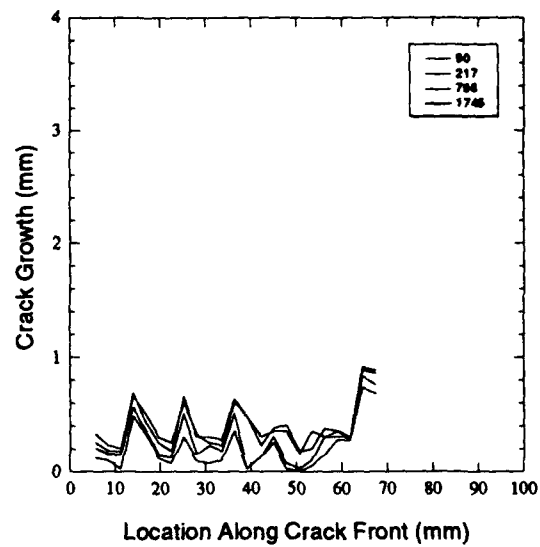
Figure 23: Fatigue Crack Growth Along Crack Front (a) Fatigue 9, (b) Fatigue 10, (c) Fatigue 11 and (d) Fatigue 15.
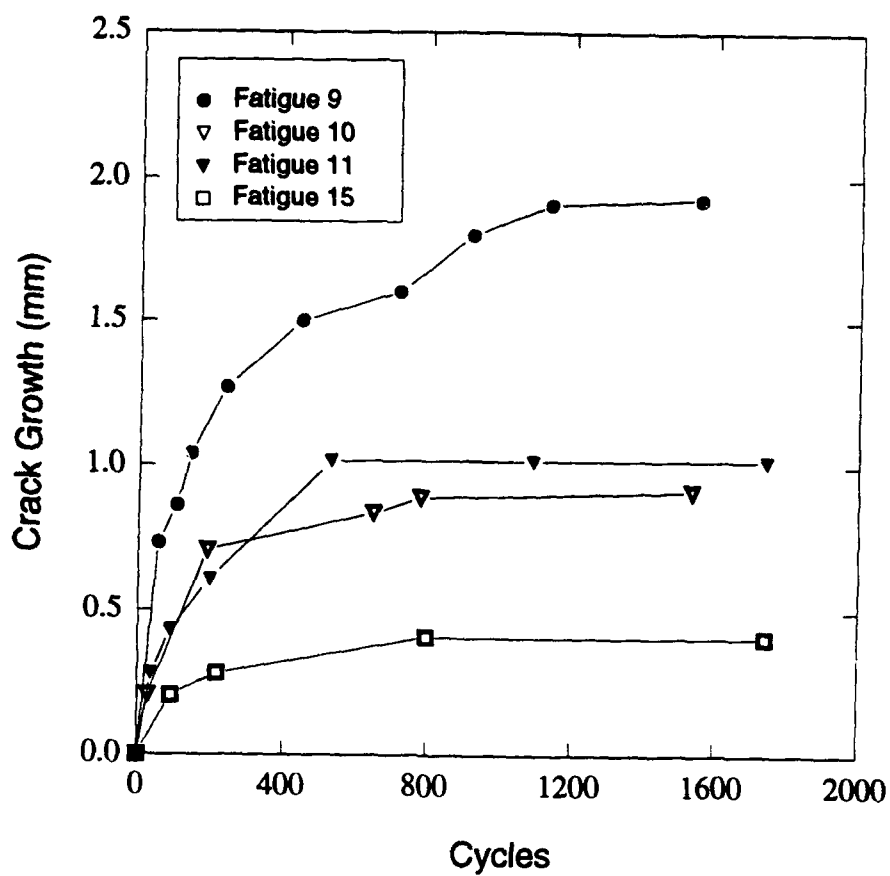
Figure 24: Fatigue Crack Growth in Ice Averaged Along Whole Crack Front

Figure 25: Micrograph of Crack Tip Region in Fatigue Test 9

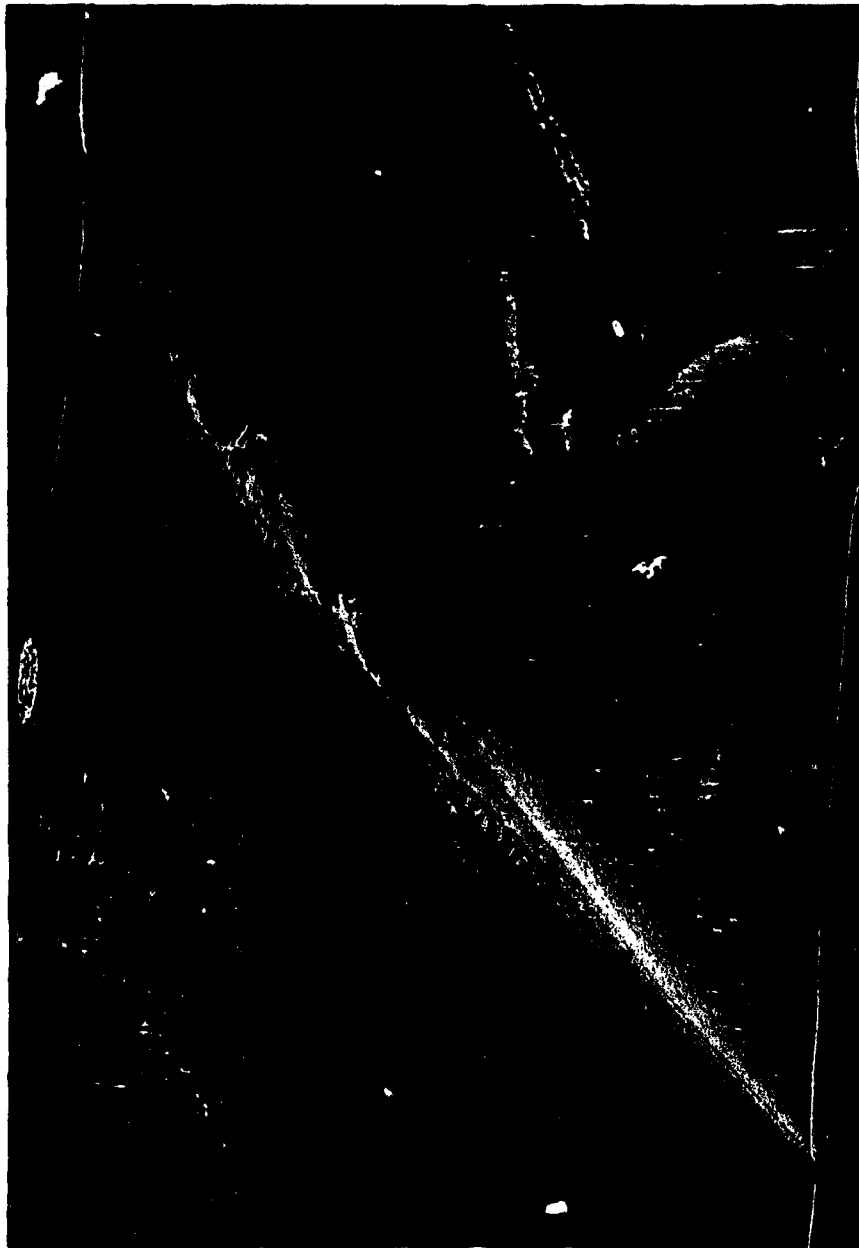Figure 26: Enlargement of Crack Tip Region, Test 9, Showing Striations

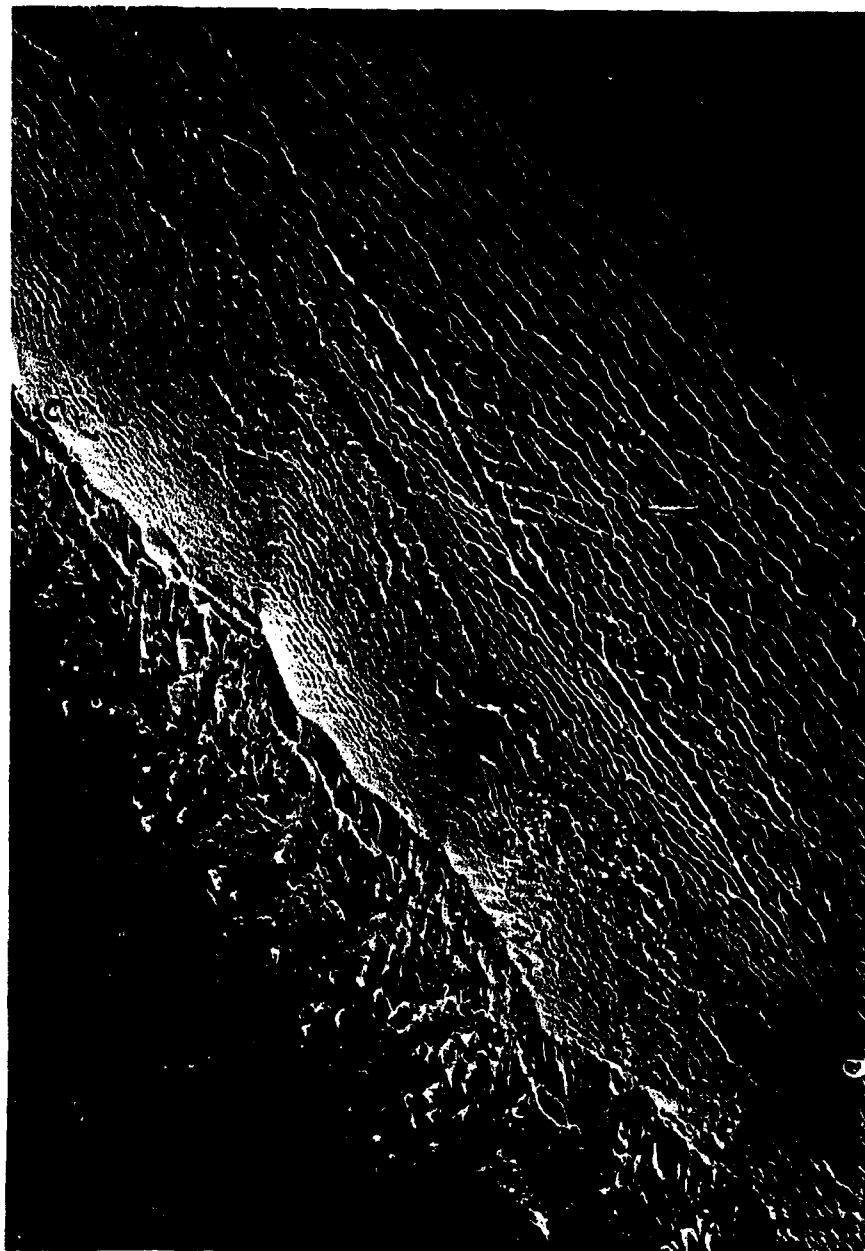Figure 27: Micrograph of Crack Tip Region in Fatigue Test 11

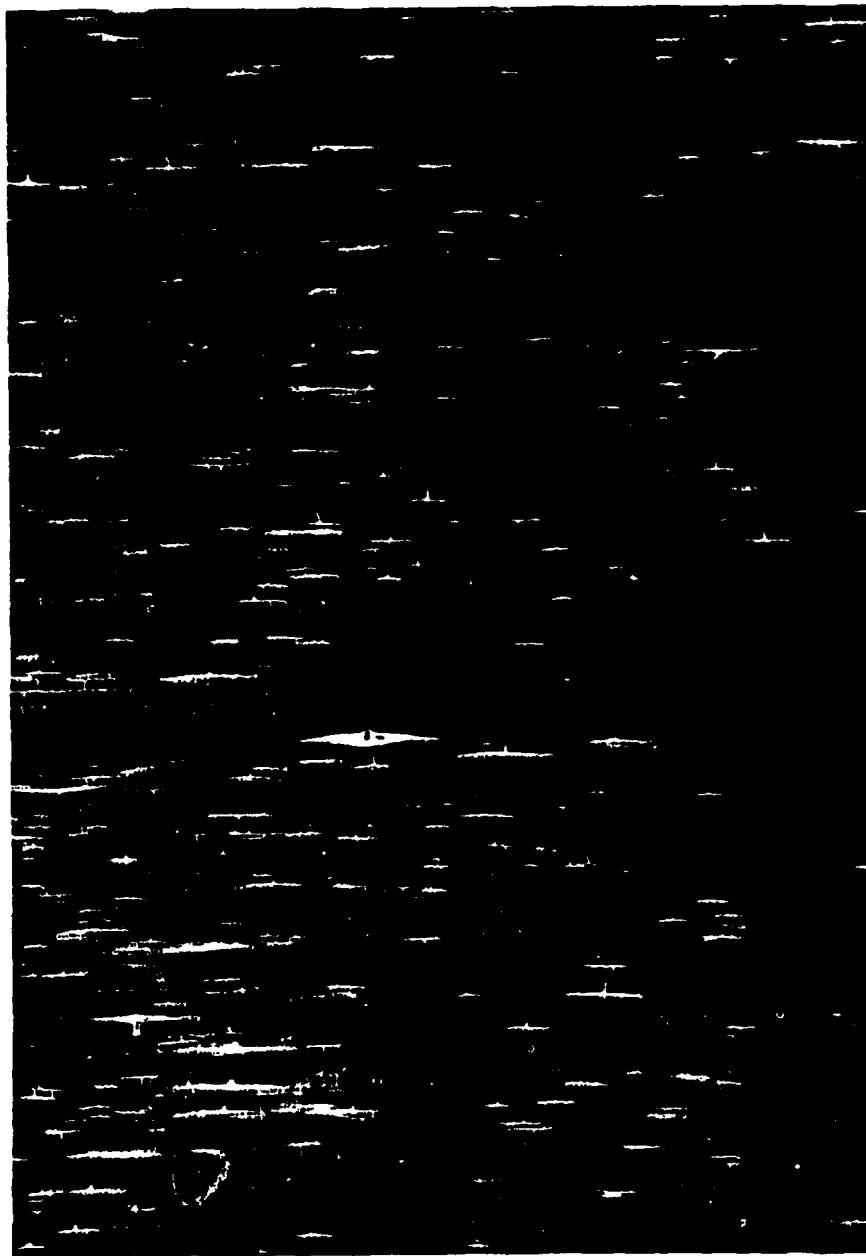Figure 28: Enlargement of Crack Tip Region, Test 11, Showing Brittle Striations

Figure 29: Region Ahead of Crack Tip, Test 9, Showing Cyclic Dislocation and Whisker